Pulse Shepherding in Nonlinear Fiber Optics

C. Yeh and L. Bergman
Jet. Propulsion Laboratory
MS 525-3660
California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109

ABSTRACT

In a wavelength division multiplexed (WDM) fiber system, where pulses on different wavelength beams may co-propagate in a single mode fiber, the cross phase modulation (CPM) effects caused by the nonlinearity of the optical fiber are unavoidable. In other words, pulses on different wavelength beams can interact with and affect. each other through the intensity dependence of the refractive index Of the fiber. Although CPM will not cause energy to be exchanged among the beams, but the pulse shapes and locations on these beams can be altered significantly.

Using this phenomenon, through the introduction of a shepherd pulse at a separate wavelength, it is possible to manipulate and control pulses on co-propagating beams. How this can be accomplished will be demonstrated in this paper.

The successful design of dispersion-shifted and dispersion-flattened optical fibers having low dispersion over a relatively large wavelength range 1.3-1.6 μm [1], enhanced the viability of multi-channel wavelength division multiplexed (WDM) system [2]. All channels will experience similar low dispersion. This design is achieved through the use of multiple cladding layers [3]. Therefore, it is conceivable that this type of multiple-cladding-layers design technique may be used to custom design the desired dispersion characteristics [4]. For example, by minimizing the chromatic dispersion over a wavelength band in which WDM channels are assigned, group-velocity mismatch for these channels may be eliminated resulting in the desirable simultaneous arrival of signals in these WDM channels. Time aligned, simultaneous arrival of WDM bit pulses is very important for a new class of bit parallel wavelength (BPW) link system used in high speed (>10 Gbyte/sec) single fiber computer buses [2].

In spite of the intrinsically small value of the nonlinearity coefficient in fused silica, due to low loss and long interaction length, the nonlinear effects in optical fibers made with fused silica cannot be ignored even at relatively low power levels [5]. This nonlinear phenomenon in fibers has been used successfully to generate optical solitons [6], 1.0 compress optical pulses [-/], to produce timing maintenance in optical communications systems [8], to

transfer energy from a pump wave to a Stokes wave through the Raman gain effect [9], to transfer energy from a pump wave to a counter-propagating Stokes wave through the Brillouin gain effect [10] and to produce four-wave mixing [11]. Now, we wish to add one more application - the shepherding effect.

In a WDM system, the cross phase modulation (XPM) effects [12, 13] caused by the nonlinearity of the optical fiber are unavoidable. These XPM effects occur when two or more optical beams co-propagate simultaneously and affect each other through the intensity dependence of the refractive index. This XPM phenomenon can be used to produce an interesting pulse shepherding effect. The purpose of this paper is to report this effect and to describe how it may be utilized to align the arrival time of pulses which are otherwise misaligned.

The fundamental equations governing M numbers of co-propagating waves in a nonlinear fiber including the XPM phenomenon are the coupled nonlinear Schrodinger equations [14]:

$$\frac{\partial A_j}{\partial z} + \frac{1}{v_{gj}}\frac{\partial A_j}{\partial t} + \frac{1}{2}\alpha_j A_j = \frac{1}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial t^2} - \gamma_j\left(|A_j|^2 + 2\sum_{m\neq j}^{M}|A_m|^2\right)A_j$$

$$(j = 1, 2, 3, \ldots M) \tag{1}$$

Here, for the jth wave, $A_j(z,t)$ is the slowly-varying amplitude of the wave, v_{gj}, the group velocity, β_{2j}, the dispersion coefficient ($\beta_{2j} = dv_{gj}^{-1}/d\omega$), α_j, the absorption coefficient, and

$$\gamma_j = \frac{n_2 \omega_j}{c\, A_{eff}} \tag{2}$$

is the nonlinear index coefficient with A_{eff} as the effective core area and $n_2 = 3.2 \times 10^{-16} cm^2/W$ for silica fibers, ω_j is the carrier frequency of the jth wave, c is the speed of light, and z is the direction of propagation along the fiber.

Introducing the normalizing coefficients

$$\tau = \frac{t - (z/v_{g1})}{T_0}$$

$$d_{1j} = (v_{g1} - v_{gj})/v_{g1} v_{gj},$$

$$\xi = z/L_{D1}, \tag{3}$$

$$L_{D1} = T_0^2/|\beta_{21}|,$$

and setting

$$u_j(\tau,\xi) = (A_j(z,t)/\sqrt{P_{0j}})\ \exp(\alpha_j L_{D1}\xi/2) \tag{4}$$

$$L_{NLj} = 1/(\gamma_j P_{0j})$$

$$L_{Dj} = T_0^2/|\beta_{2j}| \tag{5}$$

gives

$$i\frac{\partial u_j}{\partial \xi} = \frac{\mathrm{sgn}(\beta_{2j})L_{D1}}{2L_{D1}}\frac{\partial^2 u_j}{\partial \tau^2} - i\frac{d_{1j}}{T_0}L_{D1}\frac{\partial u_j}{\partial \tau}$$

$$-\frac{L_{D1}}{L_{NLj}}\left[\exp(-\alpha_j L_{D1}\xi)|u_j|^2 + 2\sum_{m\neq j}^{M}\exp(-\alpha_m L_{D1}\xi)|u_m|^2\right]u_j$$

$$(j = 1,2,3,\cdots,M) \tag{6}$$

Here, T_0 is the pulse width, P_{0j} is the incident optical power of the jth beam, and d_{1j}, the walk-off parameter between beam 1 and beam j, describes how fast a given pulse in beam j passes through the pulse in beam 1. In other words, the walk-off length is

$$L_{W(1j)} = T_0/|d_{1j}|\ . \tag{7}$$

So, $l_{W(1j)}$ is tile distance for which the faster moving pulse (say, in beam j) completely walked through the slower moving pulse in beam 1. The non] inear interaction between these two optical pulses ceases to occur after a distance $l_{W(1j)}$. For cross-phase modulat. ion (CPM) to take effect significantly, the group-velocity mismatch must be held to near zero.

It is also noted f rorn Eq. (6) t-hat. the summation term in the bracket representing the cross-phase modulat, ion (CPM) effect is twice as effective as the se] f phase modulation (SPM) effect for the same intensity. This means that the nonlinear effect of the fiber medium on a beam may be enhanced by the co-propagation of snot.}]er beam with the same group velocity.

Equation (6) is a set. of simultaneous coup] ed non] inear Schrodinger equations which may be solved numerically by the split.-step Fourier method, which was used successfully earlier to solve the problem of beam propagation in complex fiber structures, such as, the fiber coup] ers [15], and to solve the thermal b] ooming problem for high energy laser beams [16]. According to this method, the solutions may be advanced first using only the nonlinear part of the equations. And then the solutions are allowed to advance using only the linear part of Eq. (6). This forward stepping process is repeated over and over again until the desired

destination is reached. The Fourier transform is accomplished numerically via the well-known Fast Fourier Transform Technique.

Using the above approach, the evolution of all the pulses on all the co-propagating WDM beams as they propagate down the fiber may be obtained. It was through these numerical computations that we discovered the interesting pulse shepherding as well as the beam compression effects [17]. As expected these effects only exist when group-velocity mismatch for the interested beams is negligible. In other words, there is no walk-off [12] among the interesting beams. As mentioned earlier, this can be accomplished through proper tailoring of the dispersion characteristics of a single-mode fiber.

Consider now the evolution of two single pulses on two co-propagating beams whose operating wavelengths are separated by $\Delta\lambda = 4$ nm. For this case, the four wave mixing effect is negligible. It is further assumed that the signal carrying pulses on each beam are separated by sufficiently large time intervals so that no interaction among succeeding pulses on the same beam occurs. The physical parameters that are chosen for the simulation correspond to an actual system that is of interest:

L = length of fiber = 50 km

β_2 = dispersion coefficient = -1.61 ps^2/km

λ_1 = operating wavelength of beam #1 = 1.55 μm

λ_2 = operating wavelength of beam #2 = 1.546 μm

γ = nonlinear index coefficient = 20 $W^{-1}km^{-1}$

P_0 = incident power of each beam = 1 mW

α = attenuation or absorption of each beam in fiber

= 0.2 dB/km

v_g , group velocity of the beam = 2.051147 x 10^8m/sec

d_{1j} = walk-off parameter between beam #1 and beam #j

= $v_{g1} - v_{gj}$ = 0 (no walk-off)

T_0 = pulse width = 10 ps.

Using these values, the dispersion length L_D or the nonlinear length L_{NL}, which provides the length scale over which the dispersive or nonlinear effects for pulses C) in a single beam become important. for pulse evolution along a fiber of length L, is

L_D = 62 krn

c) r

L_{NL} = 50 km.

It is noted that in an idealized situation of zero fiber attenuation, soliton propagation condition for a single beam results W)"r CIF]

$$N^2 = L_D/L_{NL}$$

and N is an integer. For multiple interacting beams, there is no condition under which solitons may exist even if the fiber is lossless.

Without Shepherd Pulse

Shown in Fig. 1 (a) is the evolution of two gaussian pulses on two different wavelength beams as they propagate in this single mode fiber. These pulses are initially offset by 1/2 pulse width. It is seen that the pulses are affected by each other. Due to the nonlinear SPM and CPM effects, the pulses tend to attract each other. They appear to congregate towards region of higher induced index of refraction. The forward pulse is pulled back while the backward pulse is pushed forward so that these pulses tend to align with each other.

This observation is consistent with earlier discovery of the self-focusing effect [18] where the induced higher refraction index region caused by higher beam intensity tends to 'attract' the propagating optical wave, resulting in the 'focusing' of this optical wave. It is also consistent with the concept used to confine thermally-blooned high-energy laser beam, where multiple surrounding beams are used to

create an index environment in which the central main beam tends to expand less due to the lowering of the surrounding index of refraction caused by the heating from the surrounding beams [16]. It is also consistent with the "dragging effect" that occurs in weakly birefringent fibers [19].

It is expected, however, that when the two co-propagating pulses on two separate wavelength beams are separated by a sufficiently large distance, these two pulses will not interact with each other. This fact is demonstrated in Fig. 2(a), where the two co-propagating pulses are separated by one pulse width. Each pulse propagates independently as if it is not aware of the presence of the other pulse. It thus appears that once these pulses are launched in this manner, the separation of these pulses cannot be altered, except through the introduction of a shepherd pulse as shown in the next section.

With Shepherd Pulse

It will be shown that if another pulse, called the shepherd pulse because of its shepherding behavior on the other pulses, is launched at the right time with the right magnitude on a 1.542 μm wavelength beam which is 4 nm from beam #2 and 8 nm from beam #1, these widely separated pulses on beam #1 and beam #2, as shown in Fig. 2(a), can be brought

signi f i cantl y closer to each other. In other words, i t. i s possibl e to pul i back t he f orwa rd propa ga t. i ng pu 1 se and a t t he same time to push f orward the backward pul se to achi eve near pulse al i gnment . This i s shown in Fig. 2 (b) .

The magn i tude, the shape and the 1 ocati C) n of the shepherd pul se, al 1 cont ri bute to the event. tual success of thi s scheme to al ign these co- propagati ng pul ses . The f undamental phenomena that, govern thi s scheme are the SPM, CPM and GVD. Computer simul at-i on shows that 1 ower magni tude shepherd pul se does not possess sufficient attract ive st rength to pul l the shepherded pul ses together . For exampl e, a magni tude 1 shepherd pul se, exp (-0 .5 τ^2), situated i n the mi ddl e of the shepherded pul ses, can onl y bri ng these pul ses 1 0% cl oser to each other, whi l e a magni tude 2 shepher d pulse, 2 exp(-0.5 τ^2) , similarly situated, can almos - align these pul ses. See Fig. 2(b). It does riot. f oll ow, however , that an even hi gher magni tude shepherd pul se can bri ng t he shepherded pul ses toget her sooner, because a magni tude 3 shepherd pul se ' s tremendous ' pu] 1 ' on the shepherded pul ses tends to breakup these pul ses through the i n t. rodu ct i on of hi gher osci 11 ati ons . There j s a balance as to how strong the shepherd pul se can be .

Broadeni ng the shepherd pul se, i . e. , usi ng a 2 exp (-0.05 τ^2) pul se, only sharpens the shepherded pu 1 ses due to an i ncreased apparent. medi um nonl i neari t.y. The use of

this broadened shepherd pulse can only bring the shepherded pulses 30% closer to each other, a far cry from the alignment achieved by the sharper shepherd pulse of $2 \exp(-0.5 \tau^2)$.

The next step, perhaps, is to use two shepherd pulses on two different wavelength beams to further enhance the shepherding effect. One, the $2 \exp(-0.5\tau^2)$ shepherd pulse, on beam #3 at 1.542 μm may be used to pull the two shepherded pulses together, and the other, the $2 \exp(-0.05 \tau^2)$ shepherd pulse, on beam # 4 at. 1.538 μm may be used to sharpen the two shepherded pulses. This simulation is done. It is discovered that, the added strength of two shepherd pulses tends to breakup the shepherded pulses into several oscillating pulses, an undesirable phenomenon.

The above computer simulation shows that. there exists an optimum shepherd pulse with a certain magnitude, pulse width, pulse shape, and location with respect. to the shepherded pulses that can provide the best alignment for these pulses. For the example with the physical parameters given here, the optimum shepherd pulse appears to be the $2 \exp(-0.5 \tau^2)$ pulse situated between the two shepherded pulses.

For the case of reduced separation of the pulses to be shepherded, as for the case shown in Fig 1, a much more dramatic demonstration of the successful alignment achievable

by a wel 1 designed shepherd pul se can be seen in Fig. 1 (b). Here, the gaussian pulses on beam # 1 and C) I") beam # 2 are offset by 1/2 pulse-width. A gaussian shepherd pul se of unj ty magnitude, al i gned wi th the pul se on beam # 1, is introduced on beam # 3 whose wave] ength j s 1, 542 pm. This wavel eng th is 4 nm from beam #2 and 8 nm from beam #1, assuring that the four wave mixing effect is negligible. It is observed that this shepherd pu] se is capable of achieving excel 1 ent al i gnment for the wayward pu] se (pul se cJn beam #2) wi t h the reference pul se (pu] se on beam # 1).

Another case demonstrat i ng the ef feet. i veness of a shepherd pul se to con trol and al i gn the shepherded pul ses is shown in Fig. 3. Here, two gaussian pul ses on two di f f erent wavelength beams wi th wave] ength s of 1 .55 pm anti 1.546 μm, originating in an aligned position as shown in Fig. 3 (a), begin to separate from each ot her due to sl ight di f f erence in the group vel oci ti es for these two beams. Wi thout the presence of a shepherd pul se, these beams wi 11 be approximatel y 1/2 pul sewi dt h apart. at. SO km downstreamas can be seen from Fig. 3 (a). Wi th t he shepherd pu] se of 2 exp (-0.5 τ^2) on a thi rd beam wj th wavel eng h 1 .542 μm, ori gi na] 1 y al i gned wi th the t wo shepherded] pul ses and propagating at the same veloci ty as the pulse on beam #1, at. 50 km clown st ream, the shepherded pul ses are st il 1 al igned as shown in Fig. 3 (b).

Contrary to demanding 'fast' walk-off of co-propagating beams from each other in order to avoid any deleterious walk-off effect among the beams and to minimize the interaction among these beams due to the nonlinear behavior of the fiber medium, it is found that, by requiring as little walk-off as possible, the "shepherding" effect among the various beams may be used to "herd" them together resulting in the desirable characteristic of simultaneous arrival of co-propagating beams in a BPW (bit-parallel wavelength) system [2].

What, has been demonstrated here is that through the introduction of a shepherd pulse on a separate wavelength beam, it is possible to dynamically manipulate, control and reshape pulses on co-propagating beams. This dynamic control feature from a shepherd pulse is a unique one.

Acknowledgements

The research described in this paper was performed by the Center for Space Microelectronics Technolwy, Jet. Propulsion Laboratory, California Institute of Technology, anti was sponsored by t-he Ballistic Missile Defense Organization, Office of Innovative Science and Technology, through an agreement with the National Aeronautics anti Space Administration. One of the authors, CY, wjshes to thank Dr, w. P. Brown for his he] p in writing the solition program. .

References

1. L. G. Cohen, W. L. Mammel, and S. J. Jang, Electronics Lett. 18, 1023 (1982); B. J. Ainslie and C. R. Day, J. Lightwave Tech. LT-4, 967 (1986).

2. L. A. Bergman, A. J. Mendez, and L. S. Lome, "Bit-parallel wavelength links for high performance computer networks", to be published in SPIE Critical Review (1996).

3. C. Yeh and G. Lindgren, Appl. Opt. 16, 483 (1977).

4. H. H. Kuehl, J. Opt. Sot. Am. B 5, 709 (1988).

5. E. P. Ippen, in Laser Applications to Optics and Spectroscopy, Vol. 2, ed. by S. F. Jacobs, M. Sargent III, J. F. Scott, and M. O. Scally (Addison-Wesley, Reading, Mass. 1975) Chap. 6.

6. A. Hasegawa and F. D. Tappert, Appl. Phys. Lett. 23, 142 (1973); L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, Phys. Rev. Lett. 45, 1095 (1980).

7. L. F. Mollenauer, R. H. Stolen, J. P. Gordon, and W. J. Tomlinson, Opt. Lett. 8, 289 (1983).

8. J. P. Gordon and H. A. Haus, Opt. Lett. 11, 665 (1986); D. Woods, J. Lightwave Tech. 8, 1097 (1990); Y. Kodama and A. Hasegawa, Opt. Lett. 17, 31 (1992); L. F. Mollenauer, J. P. Gordon and S. C. Evangelides, Opt. Lett. 17, 1575 (1992); J. D. Moores, W. S. Wong and H. A. Haus, Opt. Comm. 113, 153 (1994).

9. R. H. Stolen and E. P. Ippen, Appl. Phys. Lett. 22, 276 (1973); V. A. Vysloukh and V. N. Serkin, Pisma Zh. Eksp. Theo. Fiz. 38, 170 (1983); E. M. Dianov, A. Ya. Karasik, P. V. Mamyshev, A. M. Prokhorov, M. F. Stel'makh and A. A. Fomichev, Pisma Zh. Eksp. Theo. Fiz. 41, 294 (1985) (JETP-Lett.).

10. E. P. Ippen and R. H. Stolen, Appl. Phys. Lett. 21, 539 (1972); N. A. Olsson and J. P. van der Ziel, Appl. Phys. Lett. 48, 1329 (1986).

11. R. H. Stolen, J. E. Bjorkholm, and A. Ashkin, Appl. Phys. Lett. 24, 308 (1974).

12. G. P. Agrawal, "Nonlinear Fiber Optics", Academic Press, New York (1989).

13. J. R. Taylor, Ed., "Optical Solitons - Theory and Experiment", Cambridge Studies in Modern Optics 10, Cambridge University Press, Cambridge (1992).

14. G. P. Agrawal, Phys. Rev. Lett. 59, 880 (1987)

15. C. Yeh, W. P. Brown, and R. Szejn, Appl. Opt. **18**, 489 (1979).

16. C. Yeh, J. E. Pearson, and W. P. Brown, Appl. Opt. **15**, 2913 (1976).

17. The beam compression effect due to the presence of a shepherd pulse will be discussed in a paper elsewhere.

18. F. Shimizu, Phys. Rev. Lett. **19**, 1097 (1967).

19. C. R. Menyuk, J. Opt. Soc. Am. **B5**, 392 (1988).

Figure Captions

Figure 1. Evolution of two gaussian pulses on two WDM beams, separated by 1/2 pulse width:

(a) Without shepherd pulse on the third beam.

(b) With shepherd pulse on the third beam.

Figure 2. Evolution of two gaussian pulses on two WDM beams, separated by 1 pulse width:

(a) Without shepherd pulse on the third beam.

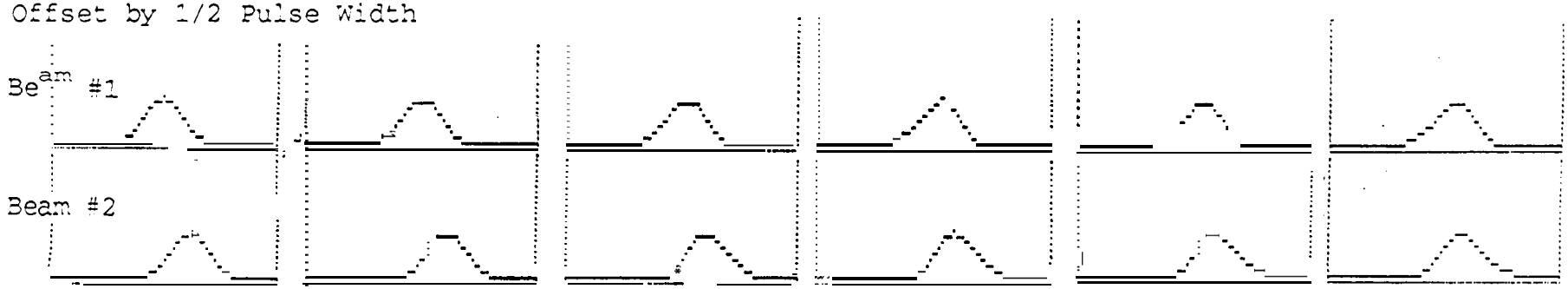
(b) With shepherd pulse on the third beam.

Figure 3. Evolution of two initially aligned gaussian pulses on two WDM beams.

(a) After propagation, separation occurs for pulses on beam #1 ant] beam #2 wi t.bout shepherd pu] se on the thi rd beam.

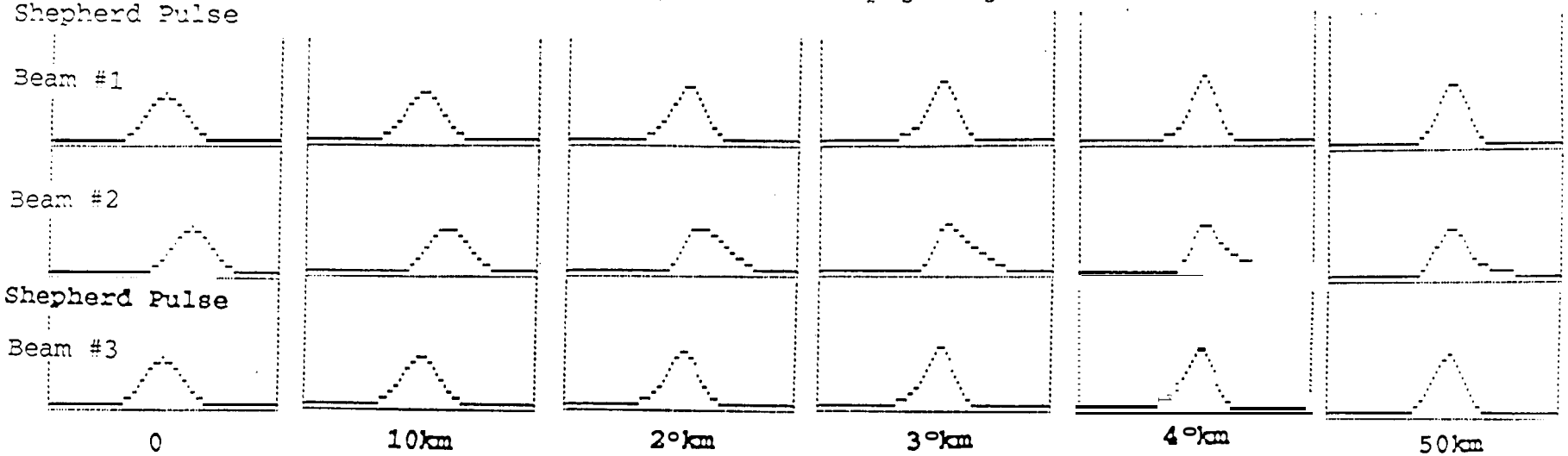
(b) Alignment maintained for pulses on beam #1 and beam #1 2 wi th shepherd pulse on the third beam.

Offset Gaussian Pulses on Dual WDM Beams
Offset by 1/2 Pulse Width



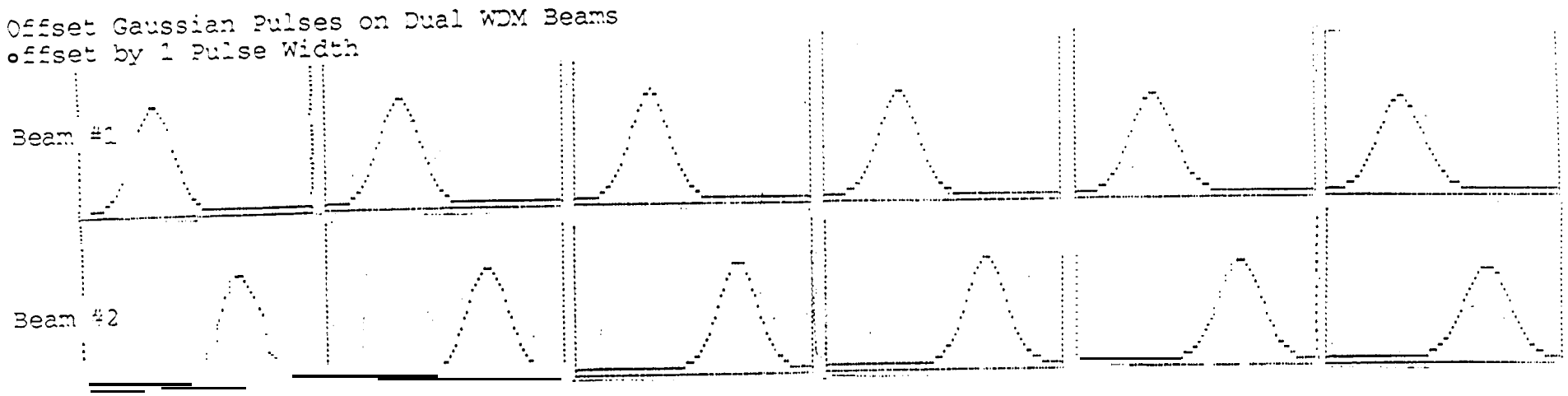
(a) Without Shepherd Pulse

Offset Gaussian Pulses on Dual WDM Beams, with Co-Propagating
Shepherd Pulse

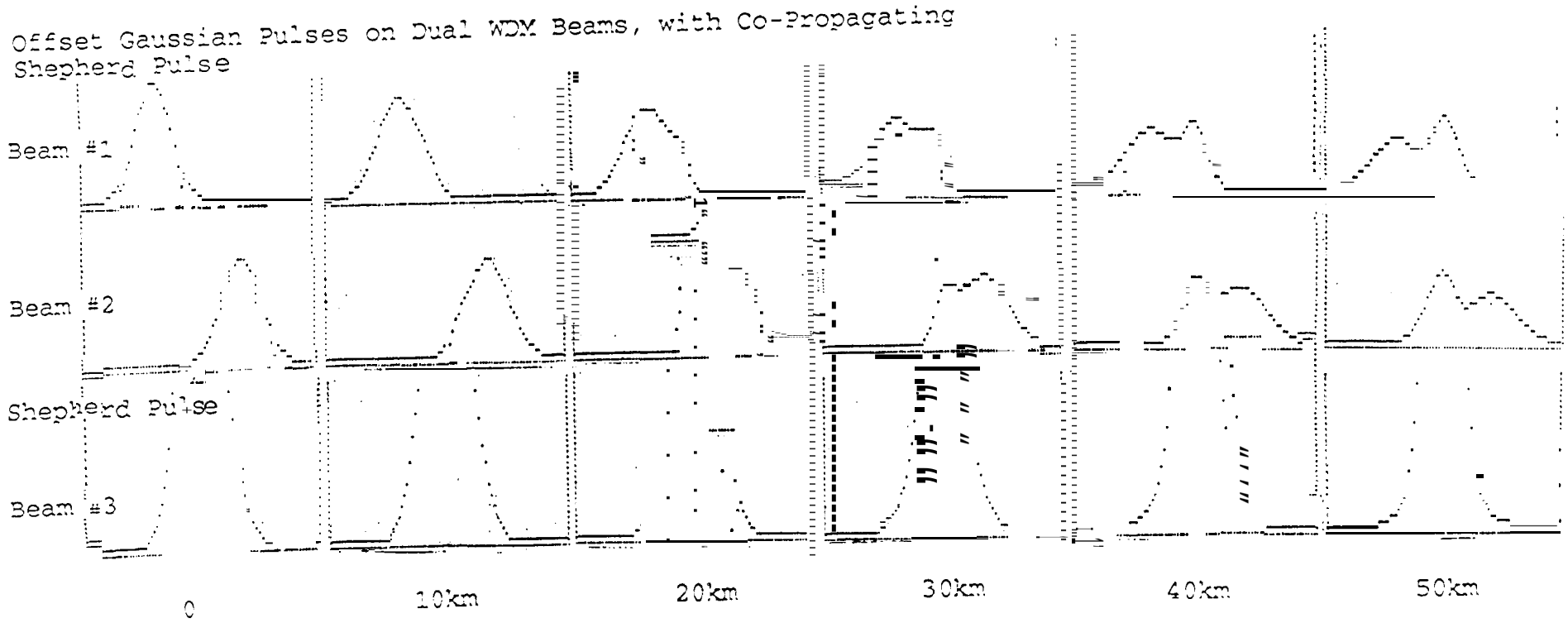


(b With Shepherd Pulse

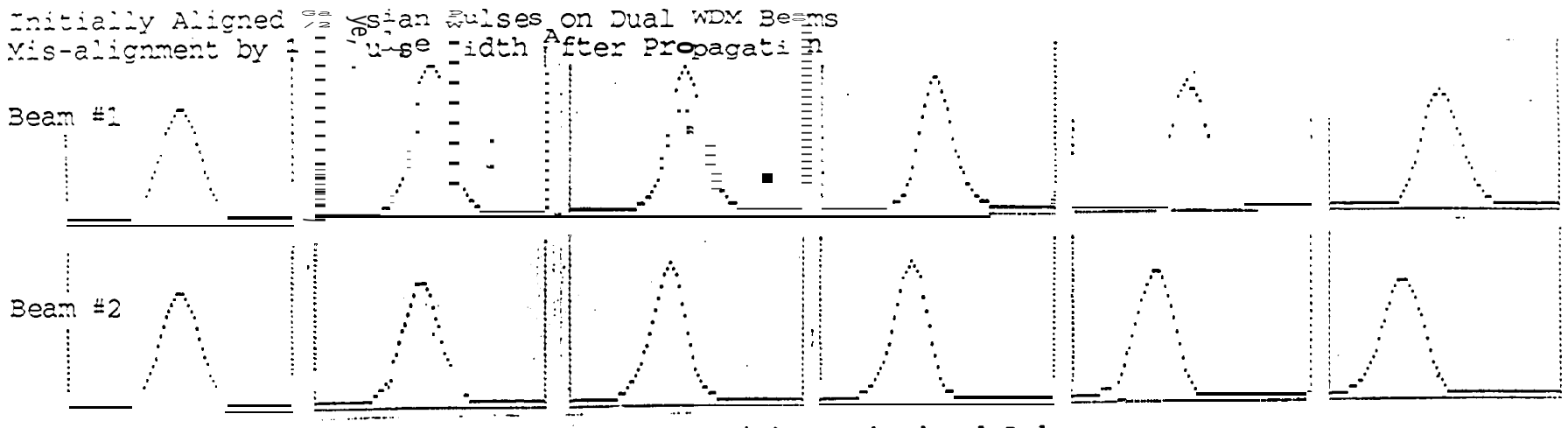
Figure 1



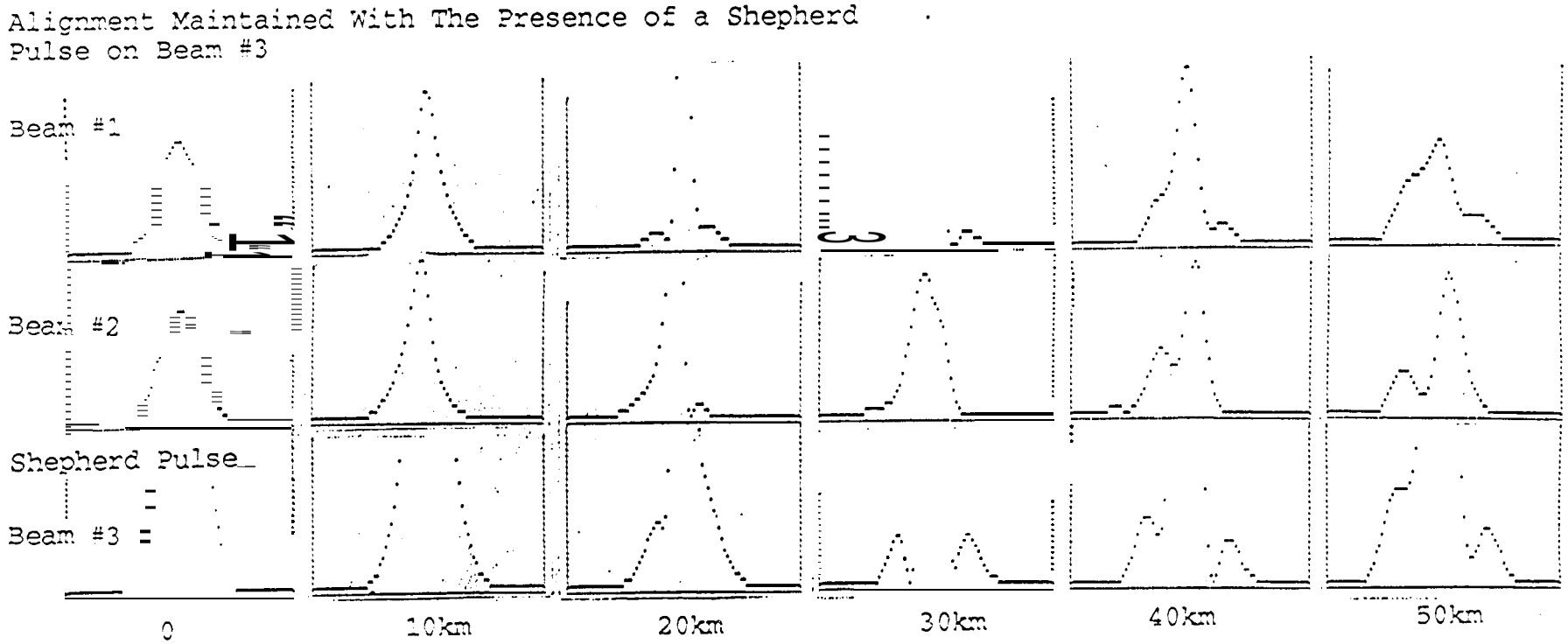
a Without Shepherd Pulse



(b) With Shepherd Pulse



(a) Without Shepherd Pulse



(b) With Shepherd Pulse

Figure 3